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SOLAR ARRAY SWITCHING POWER MANAGEMENT TECHNOLOGY FOR SPACE POWER SYSTEMS

EXECUTIVE SUMMARY

Prepared for

National Aeronautics and Space Administration

Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

Contract NAS3-22656

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16. Abstract

This report documents work performed on the Solar Array Switching Power Management Study.
Mission charactertics for three missions were defined to the depth necessary to determine their power management requirements. Solar array switching concepts were identified that could satisfy the mission requirements. These switching concepts were compared with a conventional buck regulator system on the basis of cost, weight and volume, reliability, efficiency and thermal control. For the missions reviewed, solar array switching provided significant advantages in all areas of comparison.

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EXECUTIVE SUMMARY

SOLAR ARRAY SWITCHING POWER MANAGEMENT TECHNOLOGY FOR SPACECRAFT POWER SYSTEMS

INTRODUCTION

Projected spacecraft utilization for the 1980s and beyond shows a growing trend toward extended lifetimes and larger electric power systems which require improved power control and management, and increase capability to accommodate multiple missions. It also is likely that these large space structures will utilize ion propulsion to maximize the payload mass fraction.

One method of improving power control and management is offered by Solar Array Switching Power Management (SASPM).

SASPM is an approach to power management that employs switches to directly connect groups of solar cells in such a way as to provide system voltage regulation, electrical power distribution, and the ability to reconfigure solar arrays for changing load requirements.

The objective of this study is to identify SASPM concepts and technology advancements which have the capability of increasing power systems efficiency and reducing costs. A comparison to conventional power management approaches was made, and the potential benefits of the SASPM technique in the areas of cost and weight reduction, reliability enhancement, heat rejection requirements, reconfiguration flexibility, and ease of growth were demonstrated.

For this study a set of mission characteristics were defined for the three following selected typical missions:

- Manned low earth orbiting (LEO) platform (250kW average load)
- Unmanned geosynchronous equatorial orbit (GEO) platform (50kW average load)
- Unmanned ion propulsion orbit transfer vehicle (IPOTV), 50 to 250kW load.

For each mission, an electrical power system (EPS) and power management system (PMS) were designed, using both SASPM and conventional power processing techniques. The SASPM and conventional power systems were then compared primarily on the basis of efficiency, mass, and cost.

The power transfer efficiency for SASPM was computed to be in excess of 98% for all three missions, while the power transfer efficiency for a buck regulator system was computed to be greater than 96%. The potential benefits derived from application of solar array switching power management are summarized below:

- Cost of power processing — 25 - 67% reduction
- Mass of power processing — 34 - 64% reduction
- Cost and mass of solar array — 2% reduction
- Mass of spacecraft active radiator — 6 - 12% reduction
- Cost of spacecraft active radiator — 10 - 20% reduction

It is therefore recommended that SASPM development be continued for general power systems application, and also for the high voltage application with ion propulsion. For general power systems of medium voltage (up to 200 volts), the technology is ready now. For ion propulsion, higher voltage (up to 1000 volts) is required. The necessary technology advancements that should be addressed are:

1. High voltage solar array technology, primarily in low earth orbit.

2. High voltage MOSFET technology.

Technologies that would enhance the SASPM concept are fiber optics, microprocessors, and radiation resistant solar cells.

1.0 MISSION CHARACTERISTICS

In order to determine the effects of solar array segment switching, specific parameters for the three subject missions had to be identified. The three missions identified had certain aspects in common:

- Use of a photovoltaic solar array power source
- Use of solar array switching power management
- STS launch and servicing
- 1990's technology
- Use of a dc distribution system
- High voltage (>50 Vdc) systems
- Use of ion propulsion.

A dc distribution system was chosen to minimize the number of series elements between the source and the load.

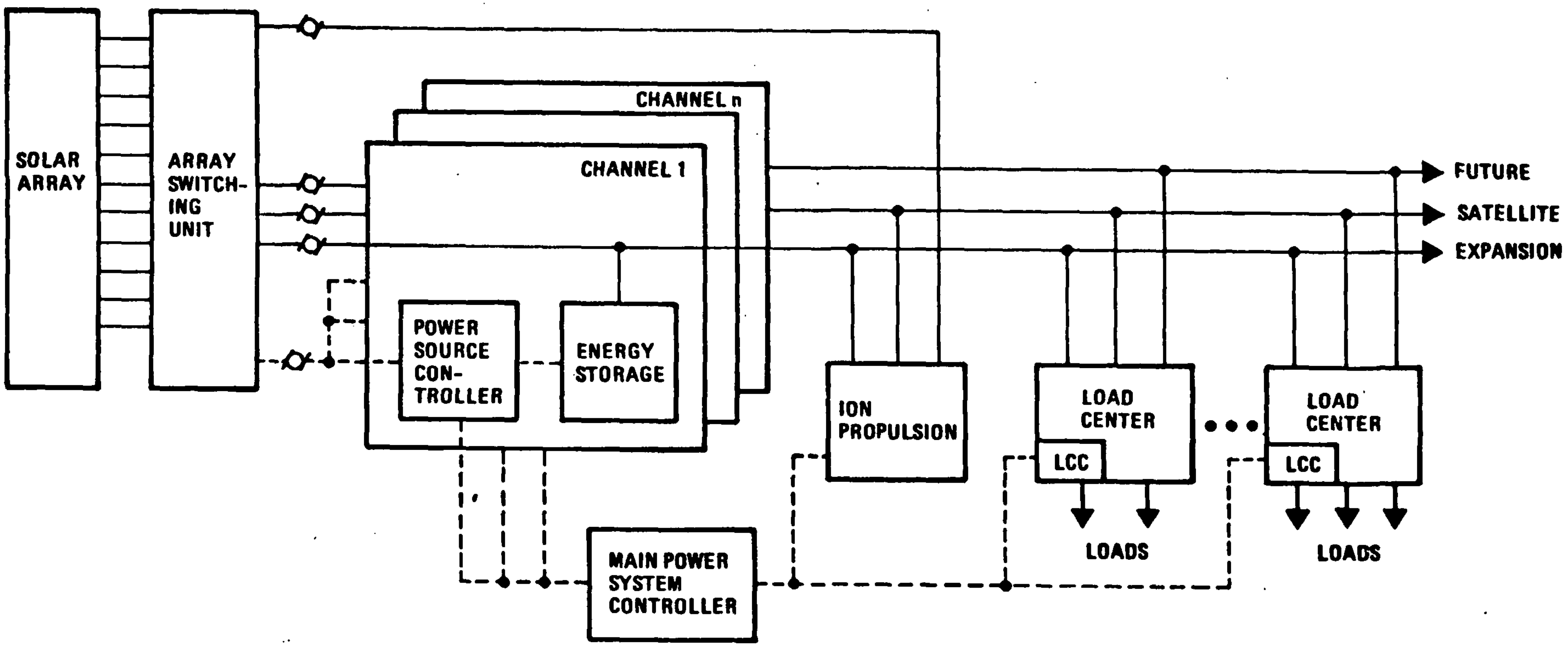
1.1 MANNED LOW EARTH ORBIT (LEO) PLATFORM DEFINITION

To minimize the atmospheric drag in LEO, and to take advantage of the possible plasma shielding capability, a concentrator solar array was selected. Nickel hydrogen batteries were selected over nickel cadmium because of the reduction in mass, and the projected less sensitive thermal requirements. Fuel cells were ruled out because of the larger solar array required to support electrolysis of the water byproduct. A single phase fluid system was chosen for thermal control because of the reduced mass over a refrigeration or a heat pipe system. A block diagram of the electrical power system is shown in Figure 1.

The power platform will be launched into LEO by the shuttle transportation system. After deployment and checkout, various payloads will be brought on-line.

The SASPM will be required to charge the nickel hydrogen batteries, while supplying power to payload and housekeeping loads (240 volts). A dedicated high voltage part of the solar array will supply, through the SASPM, high voltage power for the ion propulsion engines. This power is delivered at 800 volts during sunlight periods only.

A summary of the LEO mission characteristics is shown in Table 1.



LCC = LOAD CENTER CONTROLLER

GENERATION – CASSEGRANIAN CONCENTRATOR SOLAR ARRAY
ENERGY STORAGE – NICKEL-HYDROGEN BATTERY
BATTERY CHARGER – SOLAR ARRAY REGULATION
REGULATION – TBD
POWER TRANSMISSION – DIRECT CURRENT AT SOURCE VOLTAGE
POWER DISTRIBUTION – DIRECT CURRENT AT SOURCE VOLTAGE
POWER PROCESSING – AS NEEDED WITHIN EACH PAYLOAD OR LOAD CENTER
CHANNEL QUANTITY – DEFINED BY BATTERY CAPACITY
RELIABILITY – FAIL OPERATIONAL, FAIL SAFE
GRACEFUL CAPACITY DEGRADATION WITH FAILURES
LIFE – INDEFINITE; REPLACE FAILED UNIT AT NEXT SERVICE OPPORTUNITY (30 YEAR GOAL)

Figure 1. **LEO Baseline Electrical Power System Design**

Table 1. Mission Characteristics Summary

	LEO	GEO	IPOTV
Solar Array	Concentrator	Planar	Planar
Solar Array Reconfiguration	No	Yes	Yes
Battery (Ah)	NiH_2(250)	AgH_2(150)	NiH_2(50)
Full Charge Rate (A)	97	15	5
Trickle Charge Rate (A)	3	2	1
Voltage			
Main Bus (Vdc)	200-240	200-260	100-120
Ion Propulsion (Vdc)	800	800	800
Load Power			
Payload (kW)	250	50*	--
Housekeeping (kW)	25	5	5
Ion Propulsion (kW)	23	5-50*	50-250
Battery Charging Power (kW)	256	16	3
Minimum Useful Life (yrs)	20-30	8-10	**
Orbit (km)	≃400	--	--

*Not simultaneous

**Depends upon Van Allen belt exposure (Number of LEO-GEO trips).

1.2 UNMANNED GEOSYNCHRONOUS EARTH ORBIT (GEO) PLATFORM DEFINITION

For reasons similar to those given for the manned LEO platform, a dc distribution system was chosen, with a main bus voltage range of 200 to 260 volts. GEO missions are mass limited and, therefore, a lightweight planar array was chosen as the power source. The planar array is projected to be two-thirds the mass of a concentrator array. The increased area is not an important factor in GEO.

For energy storage silver hydrogen batteries were selected. These batteries have a higher energy density and, therefore, less mass than nickel hydrogen, and are projected to have a cycle life of 10 years in GEO. The thermal control system is the same as for LEO, the lightest weight system. A block diagram of the electrical power system is shown in Figure 2.

The GEO platform is launched into LEO, deployed, and checked out. Ion propulsion engines provide the power for transfer to GEO.

The SASPM will be required to configure the array for either primary ion propulsion or payloads. Except for housekeeping loads, the solar array is initially configured to supply high voltage to the ion propulsion system. After transfer to GEO, the major part of the array will be reconfigured to supply payloads (at 260 volts). A small part of the array will then supply high voltage for stationkeeping thrusters. Ion propulsion will operate only during sunlight periods.

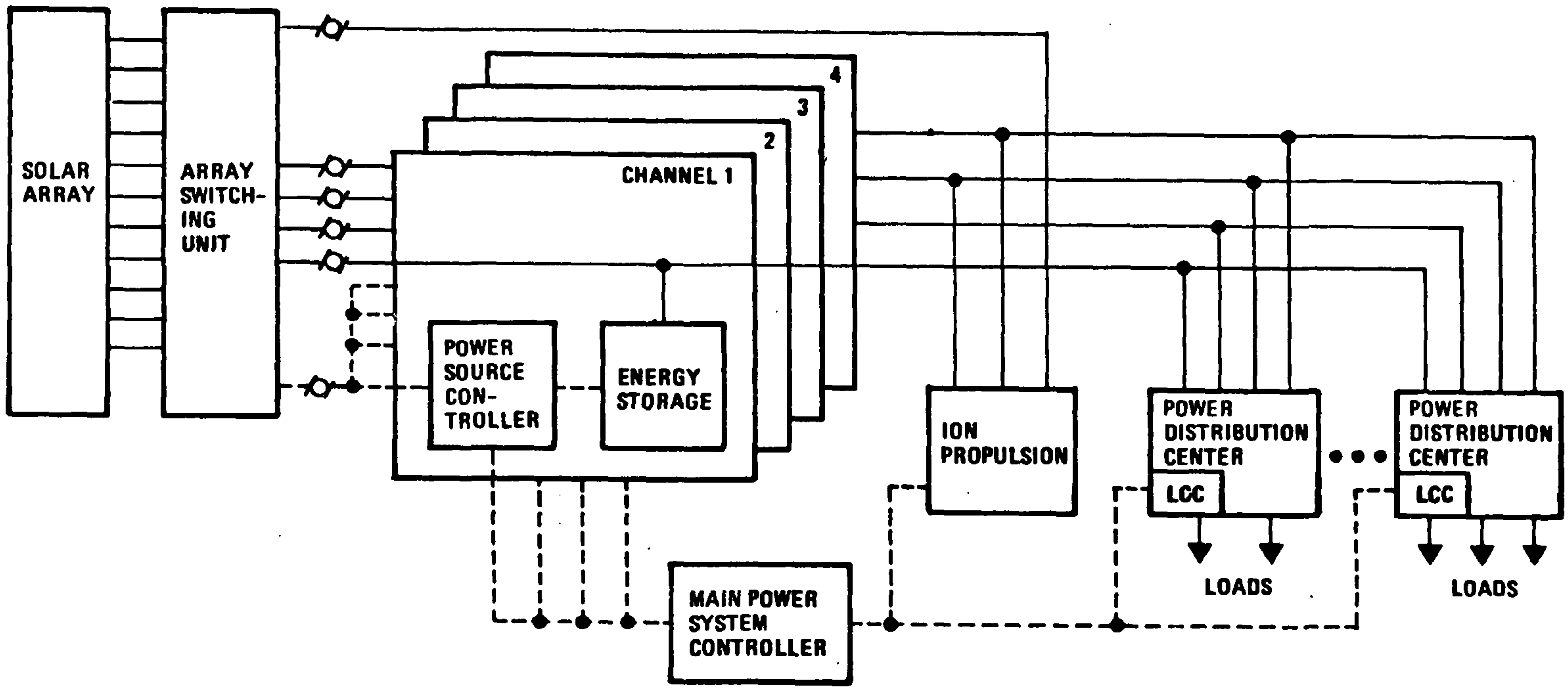
Once in GEO, the SASPM will be required to charge the silver hydrogen batteries, while supplying power to payload and housekeeping loads. For orbit relocation, payloads are shut off, the SASPM reconfigures the array to supply ion propulsion, and then reconfigures again to the original position to supply payloads.

A summary of the GEO mission characteristics is given in Table 1.

1.3 UNMANNED ION PROPULSION ORBIT TRANSFER VEHICLE (IPOTV)

As with the other two missions, a dc distribution system was selected. Since the ion propulsion only operates during sunlight, energy storage is required only for housekeeping loads (5 kW). A voltage range of 100 to 120 volts is selected for housekeeping loads.

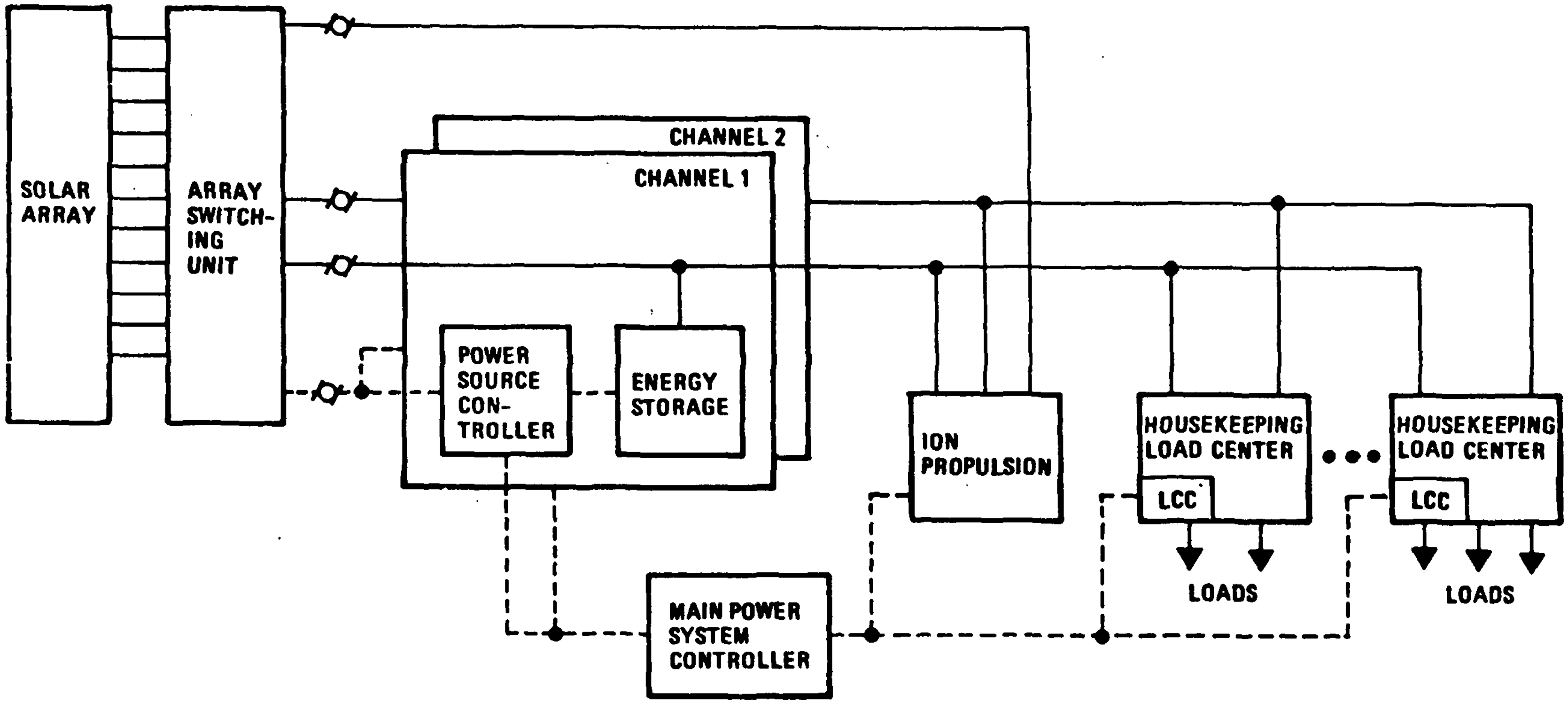
The IPOTV is mass sensitive and, therefore, a planar array was selected. Nickel hydrogen batteries were selected because of the longer cycle life. A single phase fluid system was selected because of its mass advantage over either a refrigeration or a heat pipe system. A block diagram of the electrical power system is shown in Figure 3.



LCC = LOAD CENTER CONTROLLER

GENERATION – SILICON PLANAR SOLAR ARRAY
ENERGY STORAGE – SILVER-HYDROGEN BATTERY
BATTERY CHARGER – SOLAR ARRAY REGULATION
REGULATION – TBD
POWER TRANSMISSION – DIRECT CURRENT AT SOURCE VOLTAGE
POWER DISTRIBUTION – DIRECT CURRENT AT SOURCE VOLTAGE
POWER PROCESSING – AS NEEDED WITHIN EACH PAYLOAD OR LOAD CENTER
CHANNEL QUANTITY – DEFINED BY BATTERY CAPACITY (4)
RELIABILITY – FAIL OPERATIONAL, FAIL SAFE
LIFE – 8 - 10 YEARS

Figure 2. GEO Baseline Electrical Power System Design



GENERATION – SILICON PLANAR SOLAR ARRAY
ENERGY STORAGE – NICKEL-HYDROGEN BATTERY
BATTERY CHARGER – SOLAR ARRAY REGULATION
REGULATION – TBD
POWER TRANSMISSION – DIRECT CURRENT AT SOURCE VOLTAGE
POWER DISTRIBUTION – DIRECT CURRENT AT SOURCE VOLTAGE
POWER PROCESSING – AS NEEDED WITHIN EACH LOAD CENTER
CHANNEL QUANTITY – DEFINED BY BATTERY CAPACITY (2)
RELIABILITY – FAIL OPERATIONAL, FAIL SAFE
LIFE – FUNCTION OF USAGE, REPLACE FAILED UNIT AT NEXT SERVICE OPPORTUNITY

Figure 3. **IPOTV Baseline Electrical Power System Design**

The IPOTV will be launched into LEO by the shuttle transportation system. After checkout, the array will be folded and the vehicle will dock to the manned LEO platform awaiting its first mission. The vehicle will undock, extend the solar array, dock to a payload and carry it to the desired orbit, and return to the LEO platform.

The IPOTV makes many trips through the Van Allen belt. This results in accelerated degradation of the solar array. The high voltage supply to the ion engines will be affected, and the engine will be throttled back in proportion to the power and voltage loss. Nominal high voltage for this study is 800 volts; however, it appears feasible to start out with 960 volts (four 240-volt sections) and allow the voltage to degrade to 720 volts, and then switch in another section. In this way the useful life of the array can be extended by a factor of 2. The output power capability would continue to degrade to a lower limit of 50 kW, at which time the panels would be replaced.

The SASPM will be required to supply a dedicated low voltage array section (120 volts) for housekeeping loads, and battery charging. The rest of the array will be dedicated to the ion propulsion system.

A summary of the mission characteristics for the ion propulsion orbit transfer vehicle is given in Table 1. (Page 1-3).

2.0 SOLAR ARRAY SWITCHING

2.1 SASU FUNCTIONS

The analysis of the three proposed missions shows that the SASU must accomplish several functions. First, it must provide voltage regulation for the 100 to 260 volt spacecraft buses and the 800 volt ion propulsion buses. The SASU must also provide the charge control mechanism for the spacecraft batteries which requires additional control circuitry that can be modified based on the battery state of health. For the ion propulsion application, arcing conditions can occur within the ion engines which result in a short on the ion propulsion power bus. Although the solar array is in itself current limiting, a required function of the SASU is to ensure that the solar array power can be diminished to the point that the arc is extinguished. For the GEO and IPOTV applications, solar array reconfiguration is advantageous and can be performed by the SASU. Finally, there are times when solar arrays must be deactivated at LEO for maintenance and refurbishment. This function can easily be accomplished by the SASU.

The critical parameter specifications for SASPM are listed in Table 2. These parameters can be broken into two general categories of dc or steady-state conditions and ac or time-variant conditions. The dc conditions require a monitoring and control mechanism that can control related system parameters within a certain accuracy of resolution. This requirement has a direct effect on the size of the array segments that must be switched. For example, a voltage regulation specification of 5 percent requires that the incremental change in array output capability must be small enough to maintain the 5 percent accuracy for all bus loading conditions. The ac conditions (load variations, transient response) set the requirements for the SASU to respond to perturbations in the power system. The ability of the SASU to respond to perturbations is a function of the frequency at which the sections are switched and the size of the array segments that are switched. For example, the designer must decide whether to switch four 1 kW sections at a fixed frequency or eight 500 watt sections at twice the frequency for a 4 kW load change on the bus. A review of Table 2 shows that the array sections size and the switching frequency are the two principal design parameters that must be determined in the design of a SASU. Therefore, a closer look at these two parameters is in order.

Table 2. SASPM Critical Parameter Specifications

Specification	Specification	SASU Design Parameters
	Regulation	
DC Voltage Limit	Percent	Array section size
Transient response • Turn on/off • Load/source	Percent Overshoot Time Period	Array section size Switching Frequency
Output impedance	Ohms Frequency Range	Array section size Switching frequency
Stability	Phase/Gain Margin	Switching frequency
Load Variations/ Characteristics	Watts/Time	Array section size Switching frequency
EMI Susceptibility	Vp-p/Frequency	Array section size Switching frequency
	Battery Charging/Discharging/State-of-Health	
DC Current Limit • Full charge • Trickle charge	Amperes	Array section size
Voltage Limit • Temperature compensated • Programmable	Volts, °F	Array section size
Ampere-Hour Integration	Ampere-Hours/ SOC/DOD	Switching frequency
Cell Voltage Monitoring	Volts	Array section size (dc voltage limit)
Overtemperature Protection	°F	Array section size
	Arc Protection (SEPS)	
DC Current Limit	Amperes	Array section size
Transient Response	Time Period	Switching frequency
Stored Energy	Joules	Array section size Switching frequency
	Solar Array Reconfiguration	
SEPS and S/C Bus Voltages	Volts	Array section size
Power Requirements	Watts	Array section size
Reconfiguration Time	Seconds	Switching frequency

2.2 SOLAR ARRAY SWITCH CONFIGURATION

There are four basic configurations that are possible when considering the solar array switching concept as shown in Figure 4. In the illustrated examples each solar array segment is equal in size. Each of the four basic switching configurations can also be combined with one or more of the other configurations to form many different options for the SASPM concept. The advantages and disadvantages of each of the four basic switching configurations are discussed below:

1) Series Switching-Series Array. The series switching-series array configuration bypasses unused array sections with make before break single-pole, double-throw switches in series with the segments. This concept controls the open circuit voltage of the array while the short circuit current of the array is uncontrolled. An advantage of this configuration for the ion propulsion application is that the ability to extinguish arcs is automatically incorporated in the series switching arrangement by the addition of a third switch position. Another advantage is that the stress on the solar cells due to shadows is not a problem, as discussed below. The disadvantages of this configuration are that the wiring complexity is increased, and the switchgear is larger and more complex than the other configurations. Also, the series connected switches contribute to the losses when the array power is needed. The switches are also floating, which requires a more complex drive circuit. A series blocking diode is required for eclipse periods.

2) Shunt Switching-Series Array. The shunt switching-series array configuration controls the open circuit voltage of the array by shorting series array sections. The array short circuit current is uncontrolled in this configuration. The advantage of this configuration is that the switches are open when full array power is required from the load. Therefore, this results in a highly efficient system at EOL. A disadvantage of this configuration is the number of series solar cells that can be shorted is limited. In the shorted condition, a weak solar cell (the one with the lowest short circuit current) can be driven in the

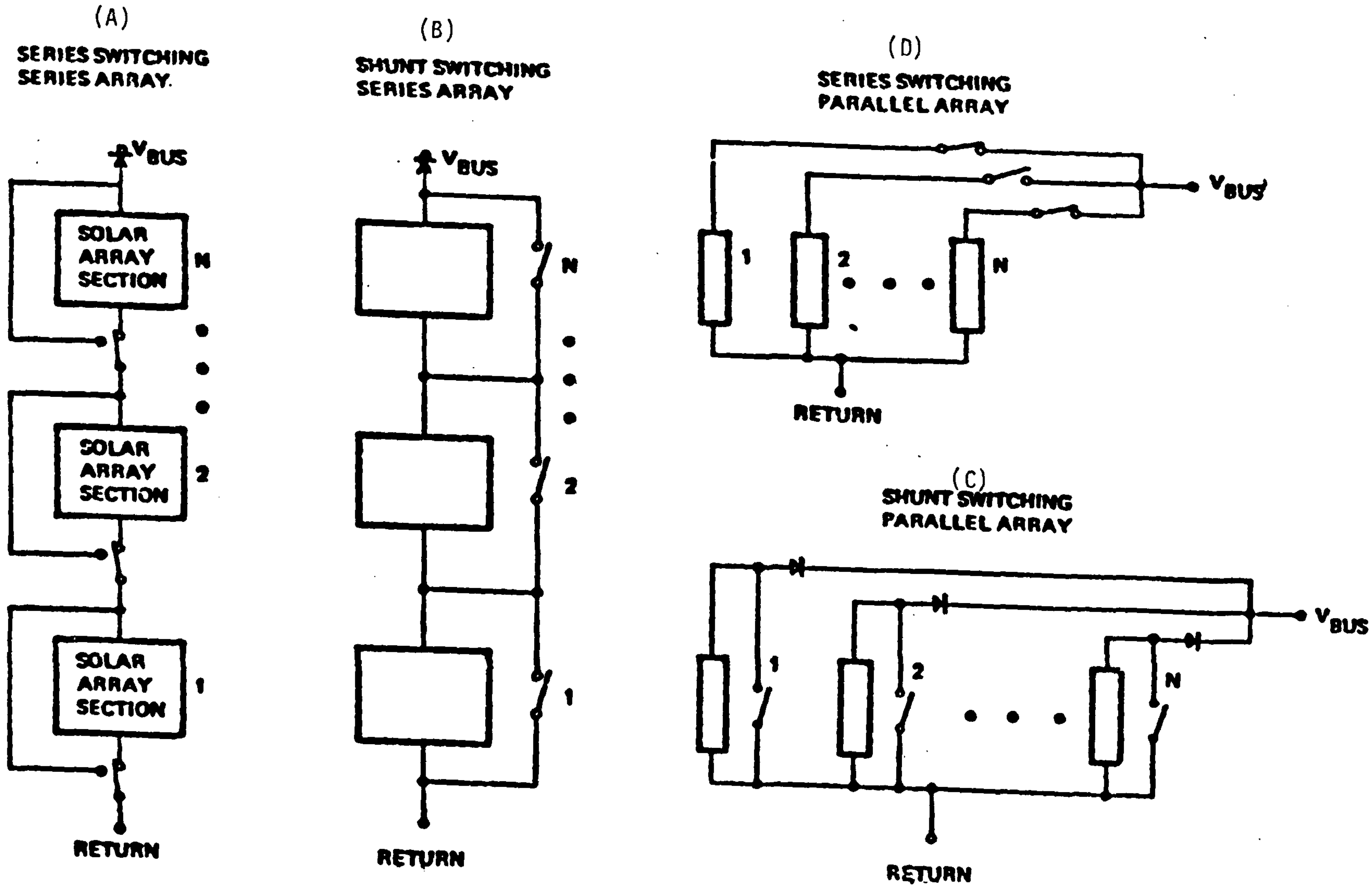


Figure 4. Basic Solar Array Switching Configuration

reverse direction, which creates overheating of the cell in the form of hot spots. This condition is especially bad if a section of the solar array is shadowed. The condition is also more apparent in the lightweight solar arrays where thermal conductivity is not as good. This configuration also suffers from increased wiring complexity and floating switches. Also, arcs may be more difficult to extinguish for the ion propulsion application, since the solar array is never disconnected from the ion engines.

3) Series Switching-Parallel Array. The series switching-parallel array configuration controls the current of the solar array by opening or closing parallel array sections. The advantages of this configuration are that the switches add no additional wiring complexity to the existing design, simple switch drive electronics can be used. since the switches may be employed at the ground level, and series blocking diodes may not be required if the switches have sufficient reverse blocking voltages. Also, the ability to extinguish ion engine arcs is automatically incorporated and there is no stress on the array due to shadowing. The disadvantage to this configuration is that the power dissipation in the switches occurs when the solar array power is needed by the loads. This dissipation is very small, however, for high voltage buses.

4) Shunt Switching-Parallel Array. The shunt switching, parallel-array configuration controls the short circuit current of the solar array by shorting parallel array segments. The advantages of the configuration are that the switch dissipation occurs during periods when excess power is available, and the switch drive electronics are simple since the switches may be employed at the ground level. The disadvantages of this configuration are that the shadowed cell stress is a severe problem since the total array is short circuited, 800 volt switchgear is required, series blocking diodes are required, and arcs may be more difficult to extinguish for the ion propulsion application since the ion engine is never disconnected from the solar array.

The series switching, parallel-array configuration has been selected for controlling the array sections that supply the spacecraft bus. Switching current sections is ideal for battery charging, and there is low stress on the solar array during shadowing. This configuration has the lowest wiring complexity, simplest switch drive electronics, and the inherent ability to extinguish in engine areas.

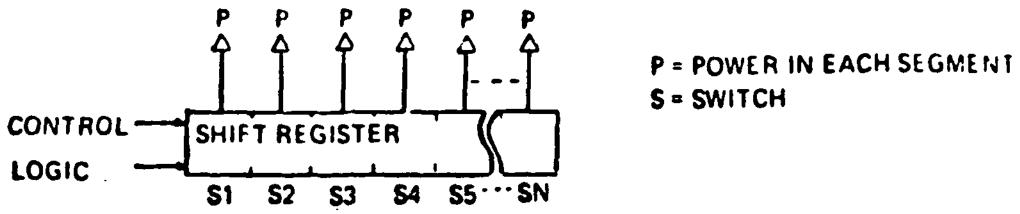
The series switching, series-array configuration was selected for high voltage ion engine control. The series array segments are ideal for voltage control in the absence of a battery. This cannot be accomplished with parallel array segments. The wiring is slightly more complex than the series switching, parallel array configuration, but the other advantages are the same.

2.3 SASU SEQUENCING APPROACHES

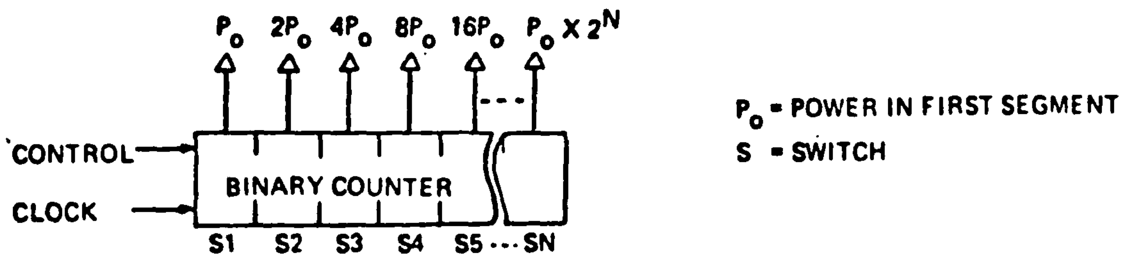
Once the switch configuration has been selected, then the manner in which the switches are sequenced must be determined. Five basic sequencing concepts were derived for the study and are shown in Figure 5. The advantages of each concept is discussed below.

1) Series Sequenced. The series-sequenced approach uses a shift register to sequentially switch each array segment. Each array segment is equal in size. The advantages of this approach are that the control method is straightforward, the stability of the feedback loop is easily determined, and a minimum number of control lines is required to the shift register. The disadvantages of this approach are that a large number of switches are required for fine control of the power bus and a high switching frequency is required for a fast transient response.

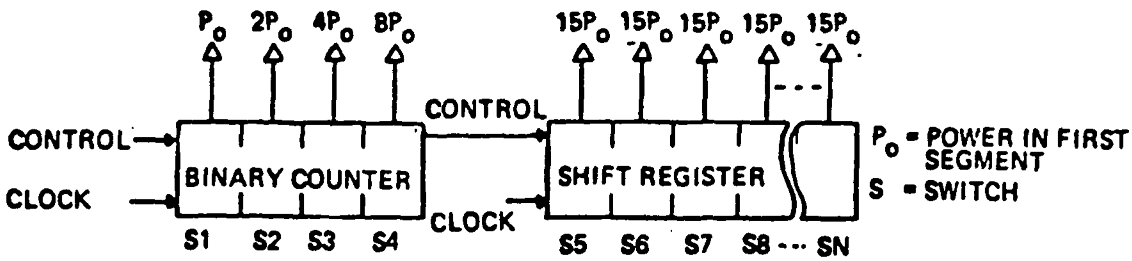
2) Binary Count. The binary count approach uses a binary counter as the sequencing device. The solar array segment sizes are binary weighted for this approach. The advantages of this approach over the series-sequenced appraoch is that the required number of switches is reduced. This approach, like the series-sequenced approach, uses a minimum number of control lines and the control method is straightforward. The feedback loop stability is also easily determined. A disadvantage of this approach is that the last segments require larger switches. Also, a very high switch frequency is required for fast response.



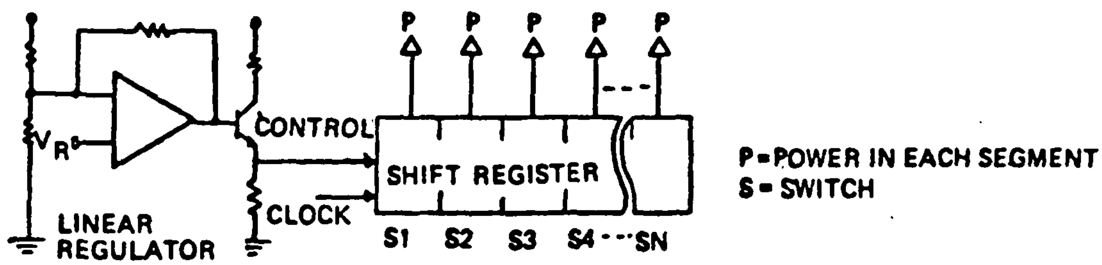
a) SERIES SEQUENCED



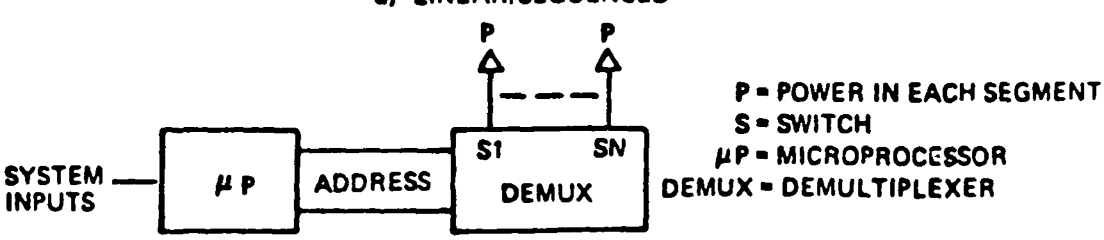
b) BINARY COUNT



c) BINARY COUNT/SEQUENCED



d) LINEAR/SEQUENCED



e) DIRECT ADDRESS SEQUENCED

FIGURE 5. **BASIC SEQUENCING CONCEPTS**

3) <u>Binary Count/Sequenced</u>. This approach combines the advantages of the shift register and the binary counter. The binary counter is used for fine control and the shift register is used to switch large segments. In this manner, the number of switches are reduced over the series-sequenced approach and the requirement to switch large power in the final section is eliminated. Like the first two approaches, this approach uses a minimum number of control lines, the control method is straightforward, and the feedback loop stability is easily determined. This approach also has the same disadvantage as the first two in that a high switching frequency is required for fast response.

4) <u>Linear/Sequenced</u>. The linear sequenced approach uses a small linear shunt regulator in conjunction with shift register. The linear regulator provides the fine control up to the power level in each array segment. An advantage of this approach is that fine control can be provided by the linear regulator with a relatively lower switching frequency in the shift register. This approach also has increased design flexibility when considering the linear and digital design tradeoffs. The disadvantages of this approach are that higher power is dissipated in the linear regulator as compared to the digital approaches and the stability of the feedback loop is more complex with the combination of linear and digital elements.

5) <u>Direct Address</u>. The direct address approach uses a microprocessor in conjunction with a demultiplexer to provide the switching control. An advantage of this approach is that several switches could be addressed simultaneously and thereby reduce the transient response time. This approach also provides the maximum flexibility in adapting to varying spacecraft conditions over the life of the mission. The disadvantage of this approach is that it is the most complex control scheme, and the stability of the feedback loop is more difficult to determine if multiple array segments were switched at varying frequencies. Also, the speed of the microprocessor could be a limiting factor in the achievement of a fast transient response.

2.4 SASPM SYSTEM CONCEPT

System concepts were derived for each of the three missions. The LEO mission concept is shown in Figure 6. Since power must be supplied to both the spacecraft and the ion propulsion system simultaneously, reconfiguration of the solar array is not necessary. Each of the power buses has its own feedback control system. The spacecraft bus feedback control measures bus voltage and battery current and controls the solar array switching unit accordingly, through the SASU control logic. A microprocessor controller measures battery state-of-health and provides battery charge control by varying the references of the voltage and current error amplifiers. The ion propulsion bus feedback loop measures the bus voltage and controls its SASU through control logic. Inputs from the ion propulsion system can modify the bus voltage and provide for arc protection.

The GEO mission concept is shown in Figure 7. Solar array reconfiguration is accommodated by a six-pole, double-throw switch. Four parallel solar array segments are reconfigured into four-series segments in this arrangement. The SASU control logic must also be reconfigured to transfer control to the desired power bus and to accommodate the new switching arrangement. The battery and bus control methods are the same as described in the LEO mission, except that the battery charge control algorithms are tailored for GEO. Reconfiguration and ion propulsion system modifications are accommodated through spacecraft level commands.

The switching concept for the IPOTV mission is shown in Figure 8. A reconfiguration concept is shown that allows for a 33 percent increase in the ion propulsion bus voltage to accommodate voltage degradation. Initially four equal solar array segments are utilized, with the fourth segment divided into three equal subsegments. The subsegments are switched in series with the remaining segments to attain the voltage increase. The monitoring and control methods are much the same as for the LEO mission.

The SASPM concept has inherent reliability in the number of switches controlling small segments of the array. A failure of a switch would reduce the peak power capability of the array, but would not otherwise affect the power processing function. A failure in a conventional regulator could result in loss of the power processing function. Redundancy in the form of parallel switches is easy to implement on SASPM, while redundant conventional regulator channels increases weight and cost rapidly.

Because of the inherent modularity of the SASPM approach, growth of the system is easy to implement. Since each array segment is separately controlled, any number of segments could be added.

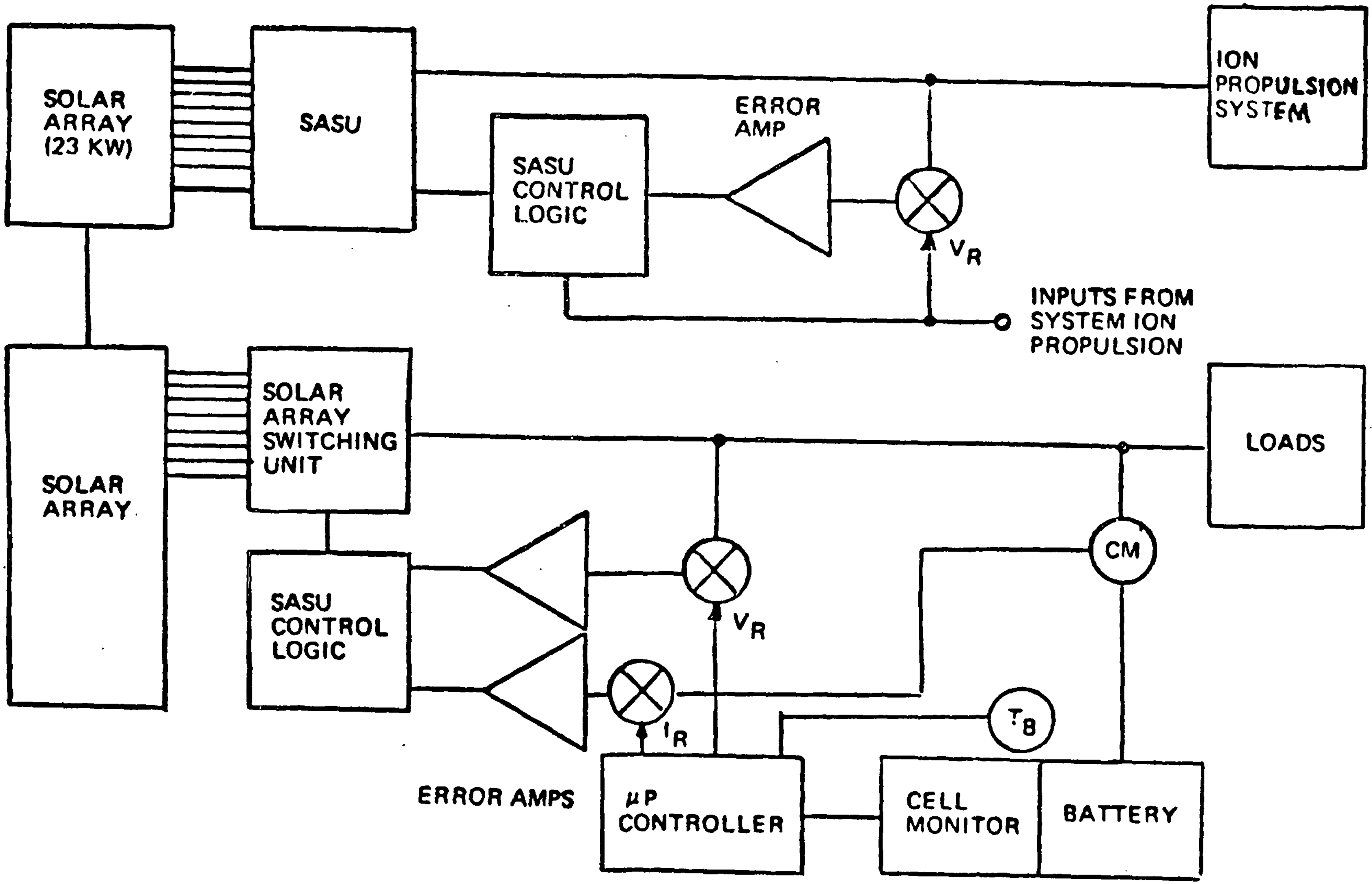


Figure 6. LEO Solar Array Switching Concept

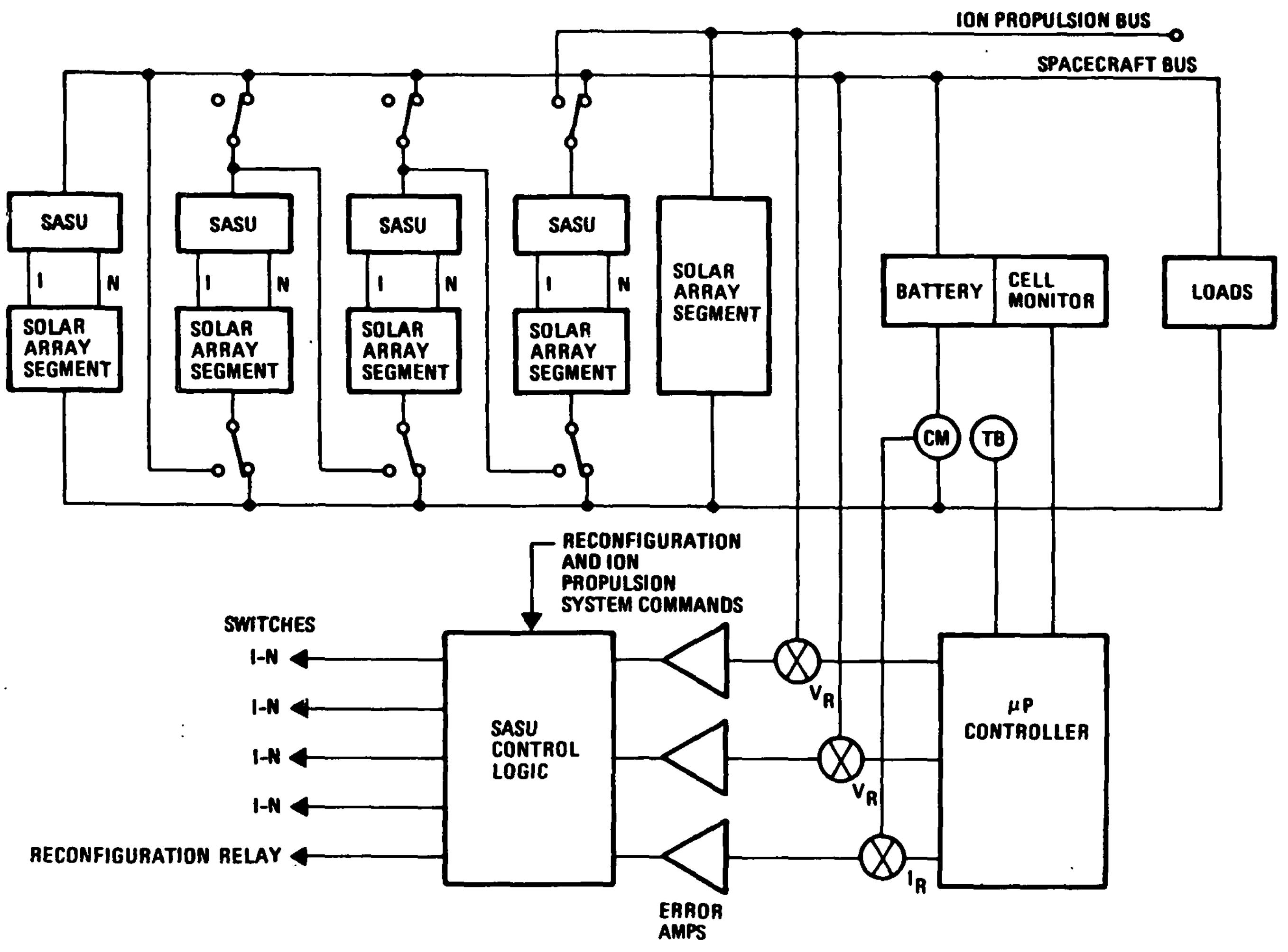


FIGURE 7. GEO SOLAR ARRAY RECONFIGURATION

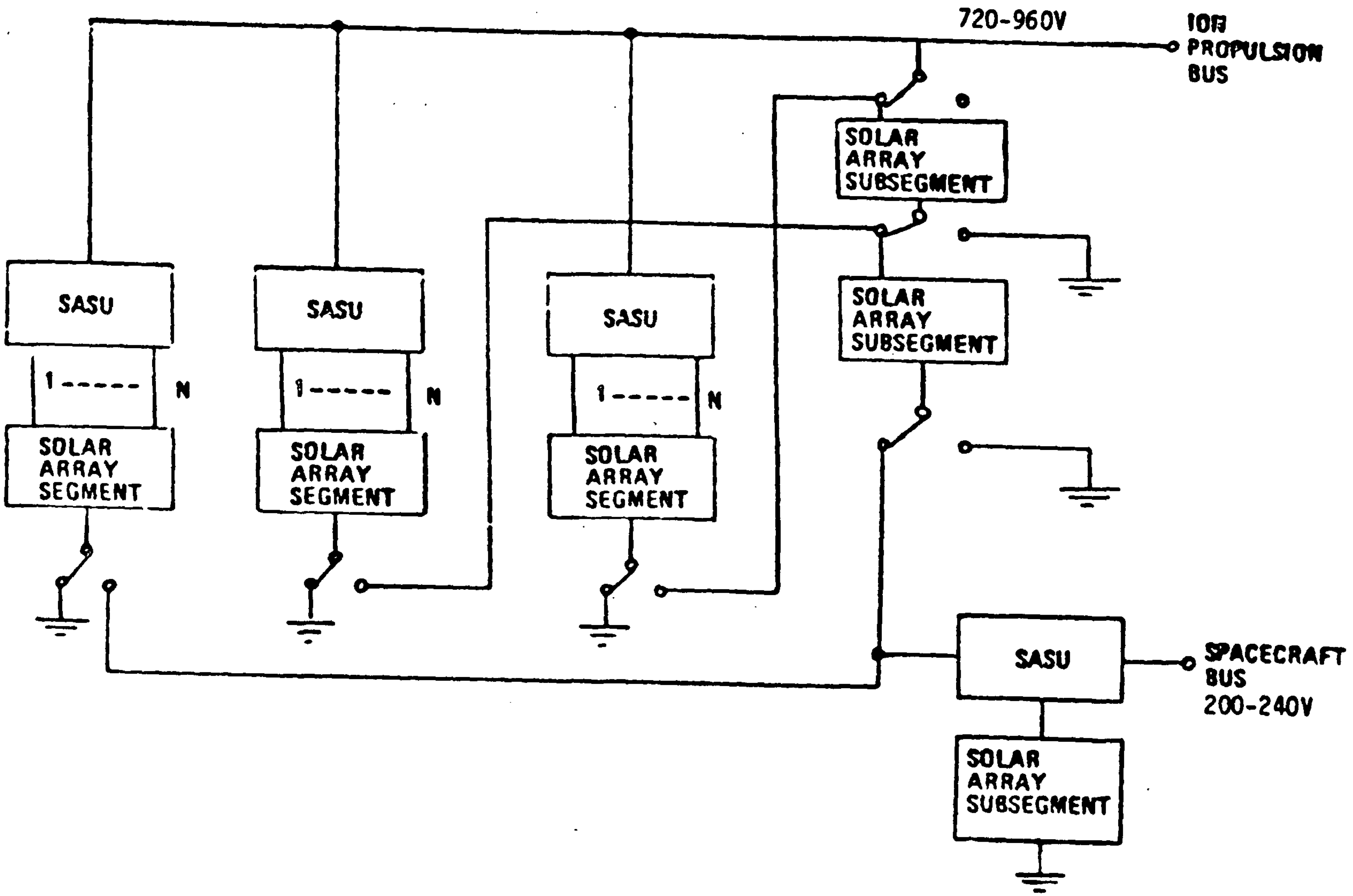


Figure 8. IPOTV Solar Array Switching Concept

CONVENTIONAL POWER PROCESSING BASELINE

Four basic conventional power processing concepts were identified:

- Transformer coupled converter (TCC) system
- Buck regulator/charger system
- Boost regulator/charger
- Shunt regulator/charger.

It was rapidly determined that the fourth candidate (a linear shunt approach) was not viable for the high power systems being considered because of excessive thermal control requirements.

Analysis showed the buck regulator system to be the lowest cost and mass system for the three selected missions.

LEO Platform Conventional System

The sizing model for the LEO platform is shown in Figure 9. Sizing of the conventional system for the LEO platform was based on the following assumptions:

- The parts count associated with the circuits reflects a non-redundant configuration.
- The weight estimate was derived based on actual TRW design, plus a reduction factor assuming a switching frequency between 20 and 30 kHz.
- Each power stage is fused to protect against internal faults.
- Overload and overvoltage protection has not been implemented.
- Conversion efficiency of 96.5 percent for the buck regulator is based on projected improvements in existing designs.

Shuttle transportation costs were derived assuming a dedicated launch with full capability utilized:

• Dedicated launch	\$30.2M
• 29,484 kg	\$1024/kg
• 65,000 pounds	\$465/pound

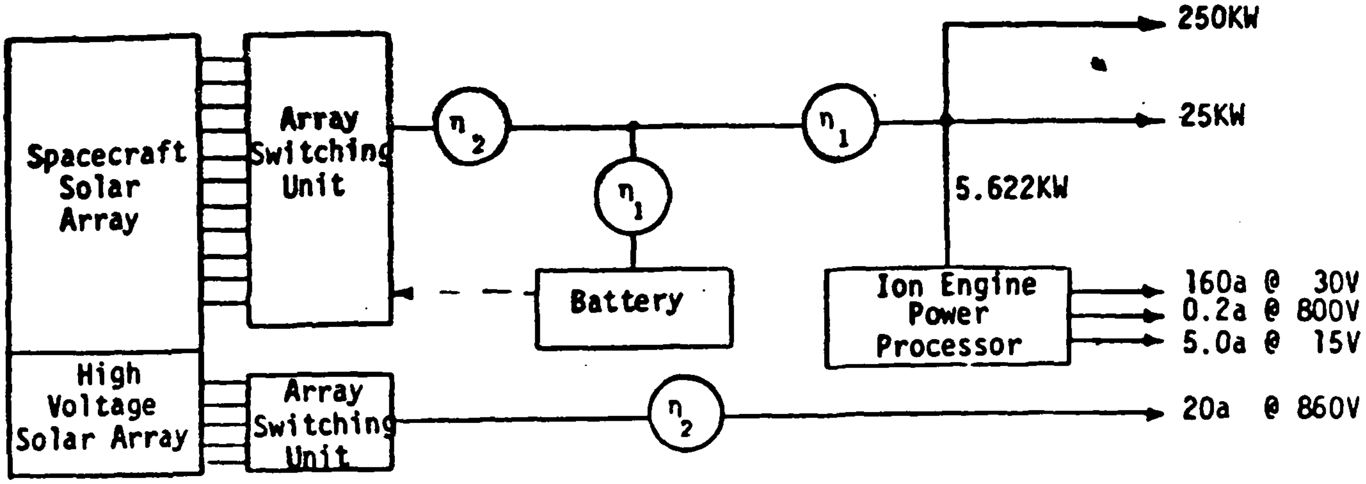


FIGURE 9. LEO Solar Array Switching Power Management EPS Sizing Model

Costs for other system elements were estimated based on the following factors:

Cassegranian Concentrator Solar Array

- Projected manufacturing cost — $30/watt
- Projected mass — 45 W/kg

Planar Solar Array

- Projected manufacturing cost — $46/watt
- Projected mass — 200W/Kg

Pumped fluid radiator

- Projected manufacturing cost — $33/watt
- Projected mass — 80.6W/Kg
- Heat exchangers — $40,000 each
- Projected mass of heat exchangers — 10 kg each
- Plumbing/engineering — $20,000/heat exchanger

Power Processors

- Projected manufacturing cost — $300/part
- Projected mass — Based on projections from existing designs

GEO Platform Conventional System

The GEO mission has two power system configurations: one for orbit transfer or orbit maneuvering, and one in which payloads are supplied the bulk of the power. The system sizing model is shown in Figure 10.

The sizing assumptions are the same as for the LEO mission.

IPOTV Mission Conventional System

The concept of the IPOTV power system was to start with a 250 kW array and use it until it degraded to 55 kW before replacing it. The system sizing model is shown in Figure 11. Sizing assumptions are the same as the other two missions.

COMPARISON OF SASPM AND CONVENTIONAL SYSTEMS

Since the buck regulator was the best of the three conventional systems analyzed, a comparison of the buck regulator system and SASPM was made. The comparison parameters for the three missions are as listed in Tables 3, 4, and 5. The following conclusions were reached as a result of this study. SASPM offers these benefits over conventional power system techniques.

- Projected reduction in the cost of power processing: 25 to 67 percent.
- Projected reduction in the mass of power processing equipment: 17 to 64 percent
- Cost and mass of the solar array was reduced 2 percent for the LEO and GEO missions. At today's cost, this range of savings would be $2M to $16M. (Projected 1990s: $.1M to $1M)
- Projected reduction in the mass of the total spacecraft active radiator: 6 to 12 percent
- Projected reduction in the cost of the total spacecraft active radiator: 10 to 20 percent.

In order to proceed with development of the SASPM concept, it became apparent that certain technology advancements were necessary. These necessary advancements are:

- Development of space-qualified, high voltage MOSFETS to accommodate the ion propulsion voltage.
- Development of space-qualified high voltage solar arrays to accommodate ion engine drive.

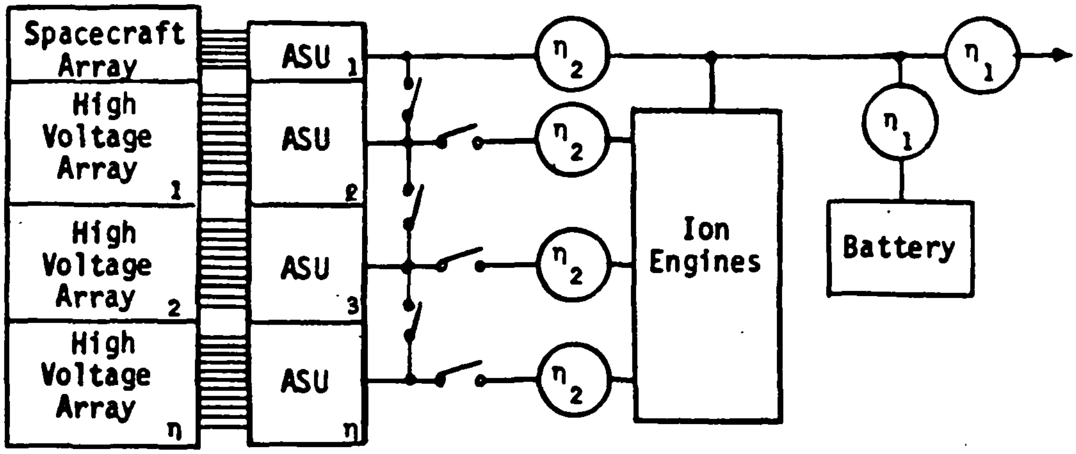


Figure 10. GEO Solar Array Switching Power Management Sizing Model

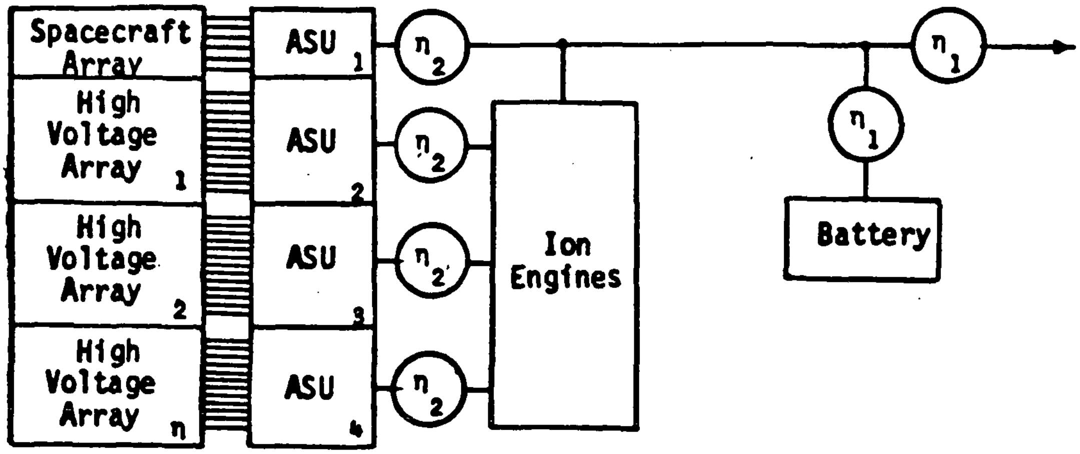


Figure 11. IPOTV Solar Array Switching Power Management Sizing Model

Table 3. LEO MISSION SIZING COMPARISON

	Buck Regulator	SASPM	Delta	%
• Mass of Processors, Kg	662	241	421	(64%)
Parts Count (Electrical)	11,193	6,898	4,295	(38%)
Cost @ $300/Part, M$	4.0	2.3	1.7	(43%)
• Solar Array Requirement, watts	702,725	687,427	15,302	(2%)
Area, square meters	4,685	4,583	102	(2%)
Mass, Kg	15,616	15,276	340	(2%)
*Cost (incl. transportation) M$	37.2	36.4	0.8	(2%)
• Active Radiator Requirement, watts	19,846	None	19,846	-
Area, square meters	44	--	44	-
Mass, Kg (incl. heat exchanger)	366	--	366	-
Cost (incl. transportation)M$	1.7	--	1.7	-
• Total Mass, Kg	16,664	15,517	1,127	6.8%
• Total Cost, M$	42.9	38.7	4.2	9.8%

* This cost is based on projected 1990's cost which is more than an order of magnitude lower than today's cost.

Table 4. GEO MISSION SIZING COMPARISON

Power Processor	Buck Regulator	SASPM	Delta	%
• Mass of Processors, Kg	109	91	18	(17%)
Parts Count (Electrical)	3,564	2,508	1,056	(30%)
Cost @$300/Part, M$ + Transportation	1.2	0.9	0.3	(25%)
• Solar Array Requirement, watts	97,666	95,588	2,078	(2%)
Area, square meters	723	708	15	(2%)
Mass, Kg	488	478	10	(2%)
*Cost, incl. transportation, M$	5.0	4.9	0.1	(2%)
• Active Radiator Requirement, watts	3,905	None	3,905	-
Area, square meters	8.6	-	8.6	-
Mass, Kg (incl. heat exchangers)	118	-	118	-
Cost (incl. transportation) M$	0.7	-	0.7	
• Total Mass, Kg	715	569	146	(20%)
• Total Cost, M$	6.9	5.8	1.1	(16%)

* This cost is based on projected 1990's cost which is more than an order of magnitude lower than today's cost.

Table 5. IPOTV MISSION SIZING SUMMARY

Power Processor	Buck Regulator	SASPM	Delta	%
● Mass of Processors, Kg	116	69	47	(41%)
Parts Count (Electrical)	5,887	1,938	3,949	(67%)
Cost @ $300/Part, M$ + Transportation	1.9	0.6	1.3	(67%)
*● Solar Array Requirement, Kw	250	250	0	--
Area, Square Meters	1,852	1,852	0	--
Mass, Kg	1,250	1,250	0	--
Cost, incl. transportation, M$	12.8	12.8	0	--
● Active Radiator Requirement, watts	10,240	None	10,240	--
Area, square meters	23	--	23	--
Mass, Kg	207	--	207	--
Cost, incl. transportation M$	1.0	--	1.0	--
● Ion Engine Initial Thrust Capability, N	3.810	5.019	1.209	(32%)
● Trip Time - First Round Trip LEO to GEO and back, days	399	312	87	(22%)
● Total Mass, Kg	1.573	1,319	254	(16%)
● Total Cost, M$	1.57	13.4	2.3	(15%)

* Solar array beginning of life capability is fixed at 250 Kw by design.

SUMMARY

The comparison of SASPM control techniques with conventional power processing techniques indicates that it is possible to reduce costs and mass of spacecraft power processing by employing the SASPM approach.

The SASPM approach has redundancy features and is inherently more reliable than conventional methods. Multiple switch failures will not destroy the function of power processing. Switches failing short will supply part of the minimum load with no effect on the system. Switches failing open will degrade the peak power performance to the extent that solar array strings are lost.

A power transfer efficienty of 98.5% is achievable using SASPM with today's technology. Higher efficiency will be possible with improvements in MOSFET "on" resistance, and the use of CMOS circuitry for microprocessor functions.

Technology is ready now for medium voltage applications (up to 200 volts). Technology and development is needed for high voltage missions. For ion propulsion, high voltage solar arrays are necessary.

A major concern is high voltage operation in LEO. It appears from work in progress at Lewis Research Center that planar array technology may not allow voltages to 800 volts. The concentrator concept may offer a solution. It may be possible to bias the reflecting cones in such a manner as to keep the plasma away from the array.